

A dynamical origin for early mass segregation in young star clusters

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ABSTRACT

Some young star clusters show a degree of mass segregation that is inconsistent with the effects of standard two-body relaxation from an initially unsegregated system without substructure, in virial equilibrium, and it is unclear whether current cluster formation models can account for this degree of initial segregation in clusters of significant mass. In this Letter we demonstrate that mergers of small clumps that are either initially mass segregated, or in which mass segregation can be produced by two-body relaxation before they merge, generically lead to larger systems which inherit the progenitor clumps’ segregation. We conclude that clusters formed in this way are naturally mass segregated, accounting for the anomalous observations and suggesting that this process of prompt mass segregation due to initial clumping should be taken fully into account in constructing cluster dynamical models.

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1. Introduction

A population of massive stars of mass m_h embedded in a cluster of stars with mean mass $\langle m \rangle$ will sink toward the cluster center on a time scale $t_{seg} \sim (\langle m \rangle / m_h) t_r$, where t_r is the cluster half-mass relaxation time scale (Spitzer 1987, Binney & Tremaine 1989). This well known process of mass segregation is a consequence of energy equipartition, whereby energy exchange between stars by two-body relaxation causes more massive stars to slow down and hence move inward in the cluster potential. Strong observational evidence for this mechanism has been found in many old globular clusters (see e.g. Sosin 1997, Sosin & King 1997, Koch et al. 2004, Pasquali et al. 2004), consistent with the fact that these systems have relaxation times significantly less than a Hubble time.

Interestingly, a number of studies also show significant mass segregation in clusters having actual ages, as measured by the evolutionary state of the component stars, substantially less than the time needed to produce the observed segregation by standard two-body relaxation (Hillenbrand 1997, Hillenbrand & Hartmann 1998, Fischer et al. 1998, de Grijs et al. 2002, Sirianni et al. 2002, Gouliermis et al. 2004, Stolte et al 2006). Numerical simulations indicate that dynamical evolution from initially unsegregated systems cannot account for the degree of mass segregation observed in these clusters (e.g. Bonnell & Davies 1998).

The obvious explanation is that these clusters were born mass segregated, and recent theoretical studies do indeed suggest that massive stars form preferentially in the centers of star-forming regions (Klessen 2001, Bonnell et al. 2001, Bonnell & Bate 2006). The mechanism invoked to explain this primordial mass segregation relies mainly on the higher accretion rate for stars in the centers of young clusters. However, the efficiency of this mechanism is still a matter of debate (Krumholz et al. 2005, Klein & McKee 2005, Bonnell & Bate 2006) and, more generally, the processes of massive star formation and feedback remain poorly understood (Krumholz et al. 2005). Simulations of cluster formation have so far been confined to small systems containing up to $\sim 10^3 M_\odot$ in stars; it is not currently known how the above findings scale to larger clusters.

In this Letter we report initial results of an extensive numerical study exploring possible dynamical routes to mass segregation during the early stages of cluster evolution. Within the context just described, we imagine that stars form in small clumps, which subsequently merge to form larger systems (see e.g. Bonnell, Bate & Vine 2003 for models of hierarchical formation of star clusters; see also Elmegreen 2006 and references therein). We assume that the clumps are either already significantly mass segregated at formation, or small enough that mass segregation can occur within the merger time scale. In either case, we find that the final clusters inherit the mass segregation of their progenitor clumps, providing a natural mechanism for the production of larger systems which are mass segregated yet physically

young. In §2 we describe the approach and initial conditions adopted in our investigation. In §3 we present our results. In §4 we summarize our conclusions and briefly describe further work now in progress.

2. Method and Initial Conditions

Our study is based on direct N -body simulations carried out using the `starlab` package⁴ (Portegies Zwart et al. 2001), accelerated by the GRAPE-6 special-purpose hardware (Makino et al. 2003, Fukushige, Makino & Kawai 2005).

For all simulations presented here, we have adopted “clumpy” initial conditions, in which the initial cluster consists of N_c clumps, their centers uniformly distributed within a sphere of radius $R_{cluster}$. (Note that we adopt terminology in which the cluster initially consists of individual clumps; alternatively, we might imagine a “super star cluster” initially consisting of individual clusters.) The system of clumps is not in virial equilibrium, and the velocities of the clump centers are negligible (zero in the simulations reported here). Our simulations have $N_c = 2$ and 4, and explore the evolution of systems having two specific values of the “clumping ratio” $\mathcal{R}_c \equiv R_{clump}/R_{cluster}$, where R_{clump} is taken to be the 90 percent Lagrangian radius of an individual clump. The two sets of runs have (i) $\mathcal{R}_c = 0.2$, corresponding to clumps that are relatively close to one another and, in some cases, effectively in contact, and (ii) $\mathcal{R}_c = 0.07$, representing clumps that are widely separated. Hereafter we refer to these choices as “moderately clumped” and “strongly clumped,” respectively.

The individual clumps are modeled as systems of 10^4 particles in virial equilibrium, with Plummer density profiles (see e.g. Heggie & Hut 2003). We present here the results of simulations with clumps comprising just two components: N_1 light particles of mass m_1 and N_2 particles of mass m_2 , with $m_2/m_1 = 20$ and $N_1/N_2 \simeq 18$. The numbers are chosen so that $m_2/\langle m \rangle \approx 10$. While a two-component mass function is obviously not representative of the IMF of a real cluster, this simplified IMF allows us to focus our attention on the essential elements of mass segregation dynamics for systems containing enough massive particles to produce statistically significant results. We note that the total mass in the massive component is unrealistically high in this case, but it yields significantly better statistics and does not affect our overall conclusions; we return to this point below.

We describe two distinct sets of simulations. In the first (hereafter called the *MS* runs), we assume that the clumps are initially mass segregated. In the second (the *NOMS* runs)

⁴<http://www.manybody.org>

the individual clumps are unsegregated—that is, both components are distributed with the same half-mass radius. Initial mass segregation in the *MS* runs is achieved by first letting a representative (*NOMS*) clump evolve in isolation for long enough for mass segregation to occur by normal two-body relaxation. We monitor the time evolution of the “segregation factor” $f_{seg} \equiv R_h/R_h(\text{heavy})$, where R_h and $R_h(\text{heavy})$ are the half-mass radii of the entire cluster and of the heavy component, respectively, and stop our calculation when f_{seg} reaches an approximate steady state (see Figure 1). This mass-segregated system is then used as a template for all clumps in our simulations. We emphasize that this procedure is just a convenient means of generating a self-consistent mass-segregated system as an initial condition for an *MS* clump.

Table 1 summarizes the simulations described in §3. The *MS* simulations are intended to explore the evolution of clusters produced from individual clumps in which initial mass segregation has already occurred due to processes acting at the time of star formation. They target the evolution of mass segregation during the merging process, quantifying the mass segregation in the clusters resulting from such clumpy systems. The *NOMS* runs, on the other hand, explore whether significant mass segregation can be produced in individual clumps before they merge, and whether that mass segregation is preserved in the final system.

N	N_c	mass seg.	clumping	N_1/N_2	Figure
10,000	1	<i>NOMS</i>	—	18, 72	1
20,000	2	<i>MS</i>	strong	18, 72	1
40,000	2	<i>MS</i>	strong	18, 72	1
40,000	4	<i>MS</i>	moderate	18	2, 3
			strong		2, 3
40,000	4	<i>NOMS</i>	moderate	18	3
			strong		3, 4
40,000	4	<i>NOMS</i>	strong	(Kroupa MF)	3
40,000	1	<i>NOMS</i>	—	18	4 (model <i>S</i>)

Table 1: Initial conditions of all simulations. The columns list (1) the total number of particles in the run, (2) the number of clumps, (3) whether or not the clumps are mass segregated, (4) the degree of clumping, (5) the ratio of light to heavy particles (for the adopted mass ratio of $m_2/m_1 = 20$, a value of 18 here corresponds to a mass fraction of 53% in the form of heavy particles; 72 corresponds to 22%), and (6) the relevant figure in the text.

3. Results

3.1. Systems with initial mass segregation (*MS* runs)

The goal of the *MS* runs is to determine whether initial mass segregation is preserved during the merger of two or more clumps and, if so, to quantify it and establish a connection between the mass segregation of the original clumps and that of the cluster resulting from the merger.

Our first sets of simulations describe a “hierarchical” merger scenario, in which two identical, initially mass-segregated clumps are placed at a separation of ten times their half-mass radius with zero relative velocity, and allowed to merge. Subsequently, two copies of the merged system are again placed at a separation of ten half-mass radii with zero relative velocity and merged. Figure 1 shows the time evolution of f_{seg} during these runs. The two panels in the figure correspond to different choices of the mass fraction of heavy stars: the upper panel has $N_1/N_2 = 18$, corresponding to a heavy mass fraction of 53%, while $N_1/N_2 = 72$ in the lower panel, for a heavy mass fraction of 22%. Both choices show qualitatively similar results.

In each panel, the first and second merger simulations are represented by solid and dashed lines, respectively. The approximate times of the mergers themselves are indicated by arrows. The dot at the end of the solid line represents the starting time and initial state of the second merger calculation. Note that this figure suggests no mass segregation at the start of each merger because the individual clumps, while themselves segregated, are initially widely separated, and the Lagrangian radii are measured relative to the center of mass of the system. The dotted lines show the evolution of a single clump in isolation, indicating the value of f_{seg} before the merger and demonstrating that internal dynamics leads to negligible structural evolution within each clump on the merger time scale. The dot at the left end of that line represents the initial condition for individual mass-segregated clumps in the next set of simulations.

In all cases, once the merger is complete, the amount of mass segregation in the final cluster, as measured by f_{seg} , is approximately equal to that in the original clumps—mass segregation is preserved during the merging process. This result is consistent with the findings of van Albada (1982) and Funato, Makino & Ebisuzaki (1992), who showed that memory of particles’ initial binding energy is not erased during violent relaxation.

Figure 2 presents the time evolution of f_{seg} for several *MS* simulations with $N_c = 4$. The dashed line shows an average of three random realizations of a moderately clumped system; the solid line shows the average of two strongly clumped runs. The dotted line at

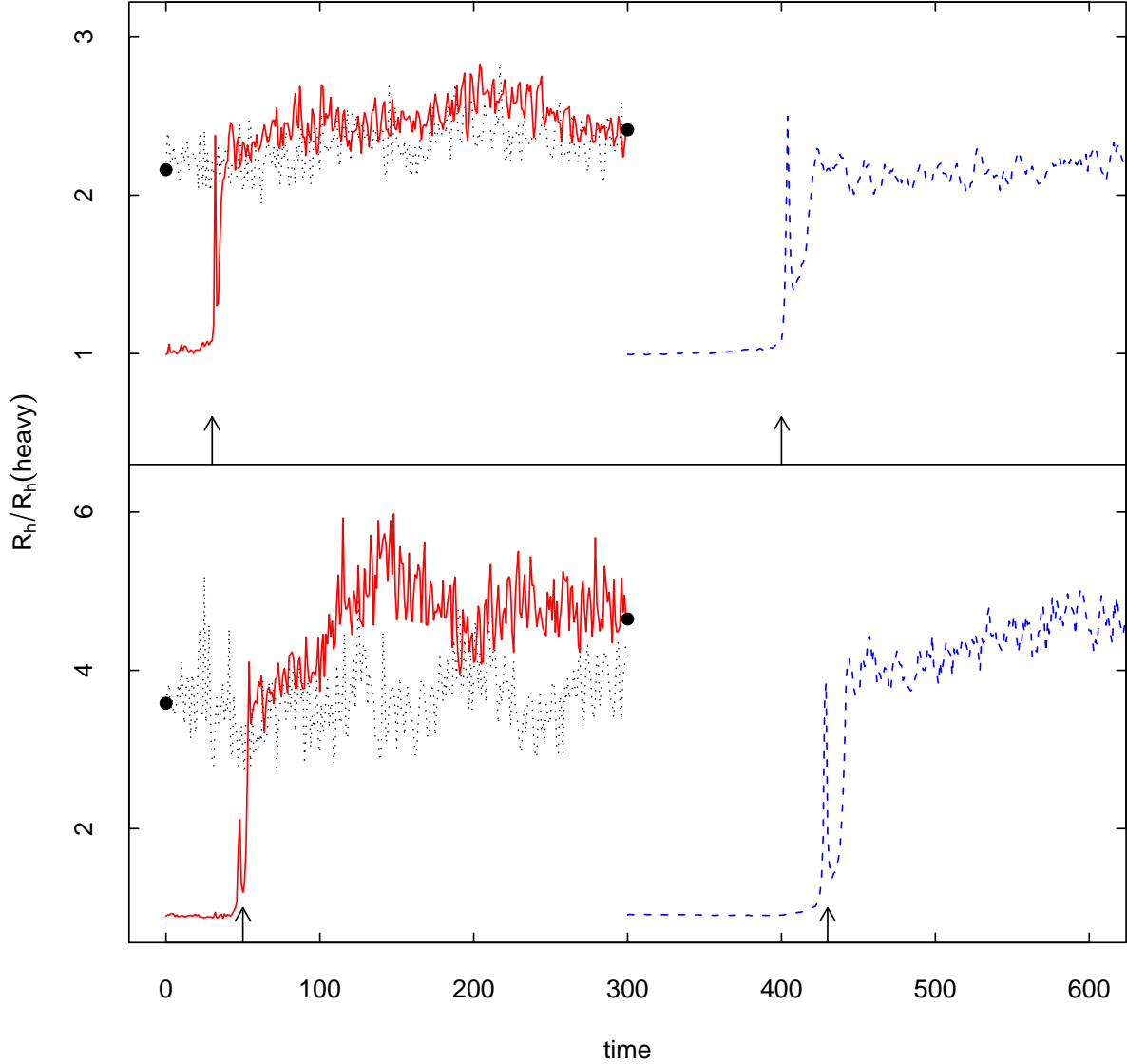


Fig. 1.— Time evolution of the segregation factor $f_{seg} = R_h/R_h(\text{heavy})$, measured relative to the system center of mass, for the hierarchical merger simulations described in §3.1. The upper panel shows results for $N_1/N_2 = 18$, the lower panel for a smaller fraction of heavy particles ($N_1/N_2 = 72$). Dotted lines show the variation of f_{seg} for the initial clumps used in the merging simulations, when evolved in isolation. Solid lines show the time evolution of f_{seg} when two such clumps merge. Dashed lines refer to the second merger simulation, in which two copies of the first merger product are allowed to coalesce. The dot at the end of each solid line indicates the state of the clumps at the start of the second merger calculation. The vertical arrows mark the times when the mergers occur. Here, as in all figures, the time unit is the dynamical time scale (Heggie & Mathieu 1986) of one of the initial unsegregated clumps used to generate the initial models.

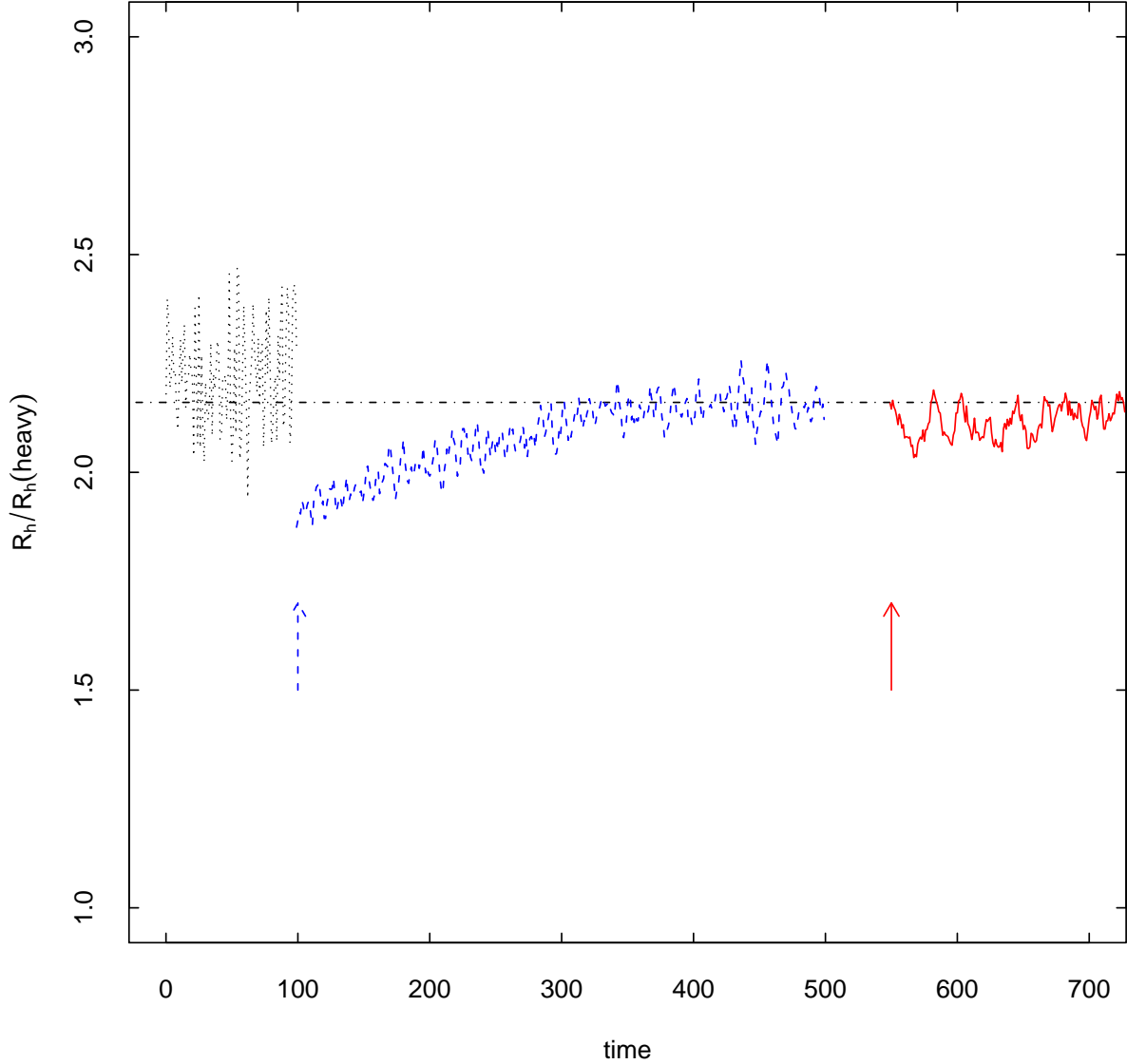


Fig. 2.— Time evolution of f_{seg} for simulations starting from 4 mass-segregated clumps (*MS* runs), for the two choices of the clumping ratio described in the text. The dashed line is for a moderately clumped initial system; the solid line is for the strongly clumped case. The dashed (solid) vertical arrow marks the effective end of the merging process for the moderately (strongly) clumped simulation (Fig. 3 shows the duration of the merging process more clearly). The dotted line shows the time evolution of f_{seg} for the initial clumps used in the merging simulations, when evolved in isolation; the horizontal dot-dashed line shows the initial value of f_{seg} in the individual clumps.

left shows a portion of the internal evolution of an isolated component clump (as in Figure 1, upper panel), as an indicator of the state of the clumps before the merger occurs. For clarity, we show the behavior of f_{seg} only after each merger is effectively complete (vertical arrows), when the merged cluster is approaching dynamical equilibrium and its center can be reliably defined.

We see that in these more general cases too, the cluster resulting from the merger inherits the mass segregation of the component clumps: violent relaxation during the merging process does not erase the memory of the clumps’ initial mass segregation.

3.2. Initially unsegregated systems (*NOMS* runs)

In order to explore whether initial mass segregation is an essential ingredient in the scenario just described, we have repeated two of the $N_c = 4$ simulations described in the previous section, but without initial mass segregation in the individual clumps. Figure 3 compares the time evolution of f_{seg} for these simulations with the corresponding *MS* simulations having the same initial distribution of clumps. In this case we follow the detailed merger history of the original clumps, to illustrate how mass segregation proceeds first within the clumps and then within each new merger product, culminating in the final merged cluster. In the moderately clumped case, individual mergers start to occur quite rapidly, even before significant internal mass segregation has occurred. In the strongly clumped case, we can clearly see internal mass segregation in some clumps before they merge. However, in both cases, the final values of f_{seg} are again comparable to those found in the *MS* simulations.

In the *NOMS* simulations, the segregation properties of the end-products are largely controlled by the ratio of t_{mrg} , the merging timescale of the cluster, to t_{seg} , the time required for internal dynamics to produce mass-segregated systems used as initial conditions in the *MS* runs. For our choice of system parameters, we find $t_{mrg}/t_{seg} \sim 0.3 - 0.5$ for moderately clumped initial conditions, and $\sim 2 - 3$ for the strongly clumped case. Thus, in both cases, the merger occurs on a timescale longer than or comparable to the mass segregation timescale of the individual clumps, so that mass segregation occurs in the clumps before the clumps merge completely, and the eventual degree of mass segregation is similar to that found in the *MS* simulations. As an additional point of comparison, the dot-dashed line in Figure 3 illustrates that the effect persists when a realistic (Kroupa et al. 1993) cluster mass function is used.

These simulations demonstrate an interesting and potentially important alternative route leading to early mass segregation in young clusters. Rather than relying on initial

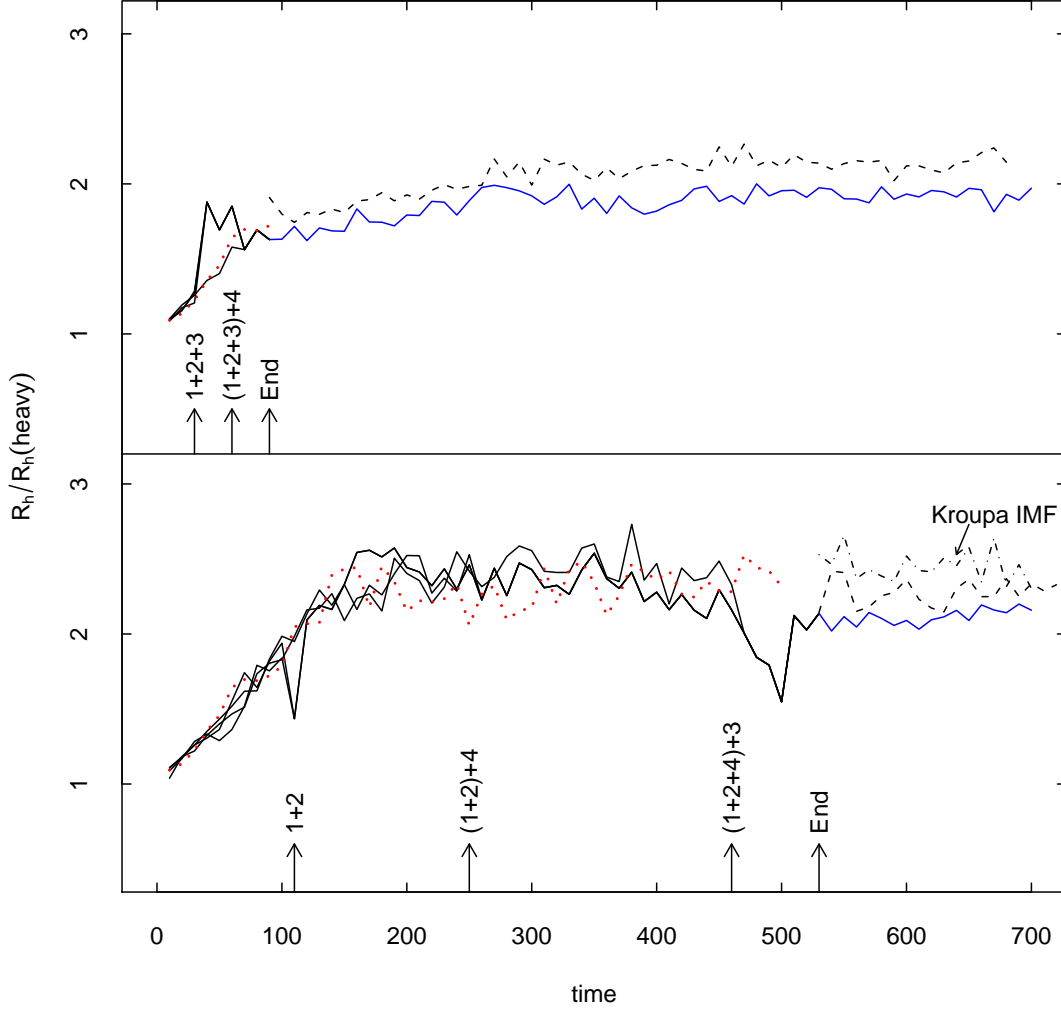


Fig. 3.— Comparison of the time evolution of f_{seg} for simulations with initially mass-segregated clumps (*MS* runs, dashed lines), and simulations starting with the same initial clump positions and velocities but without initial mass segregation (*NOMS* runs, solid lines). The upper and lower panels show data for moderately and strongly clumped initial conditions simulations, respectively. For clarity, only the final (post-merger) portions of the *MS* runs are shown. Vertical arrows mark various merging events between the clumps (arbitrarily numbered 1–4 initially); the labels above each arrow indicate the clumps involved in the merger. The rightmost arrow in each panel (labeled “End”) marks the end of the merging process, when the system is approaching dynamical equilibrium and has a single well-defined center. The solid lines at each stage of the merging process show the evolution of f_{seg} for the remaining clumps in the cluster. The dotted lines show the evolution of f_{seg} for an individual clump evolved in isolation. The dot-dashed line in the lower panel shows the results of a comparable *NOMS* simulation with a Kroupa initial mass function; in this case we plot the ratio of the half-mass radius of the whole system to the half-mass radius of stars having masses between 2.5 and 8 solar masses.

mass segregation in the clumps, this scenario hinges on the multiscale nature of the cluster early evolution: mass segregation is produced in individual small clumps, and is approximately preserved by the subsequent merging. We note that, for the *MS* runs, the merging time is the only timescale relevant to the process of forming a single large mass-segregated cluster, as the segregated cores merge rapidly once the clumps come into contact. However, for the *NOMS* runs, the additional parameter $t_{\text{mrg}}/t_{\text{seg}}$ plays a key role. For this reason, the results of the *NOMS* and *MS* runs are expected to scale differently with increasing clump and/or cluster mass.

4. Possible dynamical histories of young segregated clusters

The end products of the simulations described above are young, yet significantly mass segregated, clusters. Without knowing the actual dynamical history of the system, one might imagine “observing” one of these simulated clusters to try to reproduce its properties and reconstruct its past dynamical evolution. The traditional way to do this is to perform N -body simulations starting from the initial conditions adopted in the vast majority of numerical studies of star cluster evolution—a spherical system with no primordial mass segregation and a Plummer (or King) density profile. We have carried out this experiment, running a simulation starting from a two-component spherical system in virial equilibrium, with 40,000 particles and a Plummer density profile. Hereafter we refer to this simulation with standard initial conditions as model *S*.

Figure 4 (left frame) compares the time evolution of f_{seg} in model *S* with the strongly clumped *NOMS* run described in §3.2. As just discussed, mass segregation occurs much sooner (at least a factor of $\sim 7-10$ faster) in the clumped case. As shown in the right frame, the density profiles at the ends of the two runs, when the clusters exhibit approximately the same amount of mass segregation, are very similar. Since model *S* takes much longer than the *NOMS* system age to reproduce the same cluster properties, one might incorrectly conclude from this numerical study that the mass segregation found in this cluster must reflect its initial conditions. However, as we have shown, several possible dynamical histories can lead to similar final systems.

5. Conclusions

We have presented the results of simulations following the early evolution of star clusters, exploring the origin of mass segregation observed in young clusters. Our simulations started

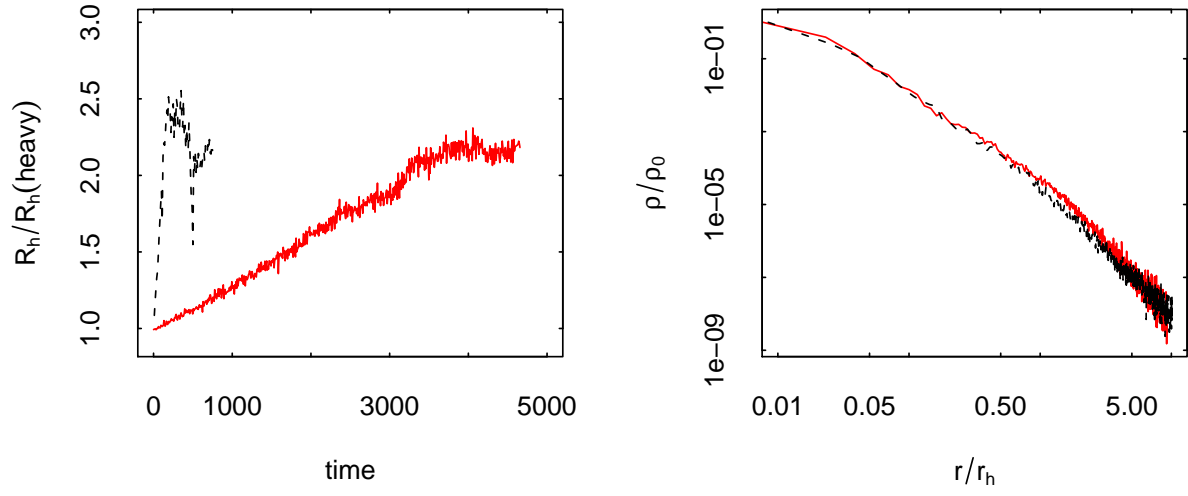


Fig. 4.— (Left) Time evolution of f_{seg} for the two simulations discussed in §4. The left (dashed) curve began from strongly clumped *NOMS* initial conditions with $N_c = 4$ (see the lower panel of Figure 3); the right (solid) curve from a single unsegregated Plummer profile. (Right) The density profiles of the two runs at the end of the simulations are almost indistinguishable.

from clumpy initial conditions with and without initial mass segregation in the individual clumps, and studied the properties of the resulting merged cluster. Our main conclusions are:

1. For clumps with initial mass segregation, the degree of mass segregation in each clump is largely preserved during the merging process.
2. For clumps without initial mass segregation, the individual clumps may become mass segregated by two-body relaxation before the clumps merge. In this case too, this mass segregation is subsequently inherited by the resultant merged cluster.
3. For clumped initial conditions, with or without initial mass segregation, the end-products of our simulations are young clusters whose properties are inconsistent with an initially unsegregated equilibrium cluster model.

Our simulations demonstrate that there are a number of viable evolutionary paths, relying on initial mass segregation in clumpy systems and/or on multiscale dynamical evolution, that can lead to a significant level of mass segregation in a physically young cluster. (See also Vesperini et al. 2006 for a further dynamical mechanism potentially leading to initial mass segregation.)

The results reported in this Letter cover only a small portion of the possible initial conditions for the clumpy systems of interest here. The full parameter space has many dimensions, spanning both the properties of individual clumps (density profile, stellar IMF, number of particles, virial ratio) and the properties of the larger system of clumps (density profile, velocity distribution, clumping ratio, number of clumps, clump mass distribution). A systematic investigation of the initial parameter space and the effects of early mass segregation on the long term evolution of clusters is currently in progress; the results will be presented elsewhere (Vesperini et al. 2006, in preparation).

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